Technical Note N-1281

DESIGN CONSIDERATIONS FOR SEAFLOOR FOUNDATIONS ON ROCK

By

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ABSTRACT

The report identifies those rock foundation concepts most likely to succeed. Existing rock foundations are first described, previous peripheral studies are reviewed, and then a brief geologic review is made of seafloor rock characteristics. It is concluded that high resolution bathymetric information is essential to successful structure emplacement. For those sites where the slope is greater than ten degrees and the microrelief is in excess of three feet, deadweight/clump foundation/anchors should be used; otherwise the proper choice is a simple three-tined (legged) foundation framework.

INTRODUCTION

Many potential seafloor structure locations consist of exposed rock or rock with a thin sediment cover. The design of a fixed, bottom-resting structure in such an environment poses a substantial problem because of the unevenness of the bearing surface and the usual accompanying strong currents.

It is the purpose of this report to: (1) identify probable locations of exposed and "near-surface" seafloor rock; (2) describe the rock surface microrelief or roughness and the rock mass integrity; and (3) examine and criticize rock foundation concepts. The first two purposes were fulfilled via a literature review, the third via preliminary analytical work and qualitative examination.

This report assumes a general knowledge of seafloor topographical terminology; when clarification is required the reader is referred to more complete texts such as References 1, 2, and 3. Reference 4 contains a good terminology summary oriented toward foundation engineering.

BACKGROUND

Usually, rock appears on ridges, topographic highs, and upper surfaces of seamounts; in trenches, canyons, and fault scarps; and on nearshore shelves, banks and terraces. But it is probable that outcroppings of nearly all magnitudes occur throughout the entire range of underwater environments. Rock relief above existing sediment surface varies in height from a few centimeters to thousands of meters. The Navy has placed some structures on these rock surfaces and has conducted studies to delineate their microrelief.

Case Histories

The Navy has used foundations on seafloor rock when strategically necessary. For example, structures are sited atop seamounts instead of the adjacent abyssal plain either because of more favorable handling and working conditions at the shallower water depths or because of the more favorable acoustic view. Similarly, structures near a seacoast are often established on rock simply because of functional geographic location requirements or because of constraints imposed by support facility location.

References 5 and 6 describe seafloor foundation case histories, some of which were on rock. For instance:

(1) The hydrophones of the Barking Sands Tactical Underwater Range (BARSTUR), Hawaiian waters, cover a 5- by 10-mile area with

water depths from 2,200 to 5,500 feet. Seventy percent of the seafloor is covered by a thin veneer of sand, the remaining 30% by outcrops of basaltic rock.[5] (See Figure 1 for hydrophone configuration.)

(2) The Azores Fixed Acoustic Range (AFAR) includes three tower structures bearing on the basaltic rock tops of seamounts in the Azores group. The towers are 120 feet high resting on an 8-foot square base plate and held upright by buoyant upper sections. The 8-foot square plate has at each of its corners a vertical spiked post; the set of four posts are capable of some load re-distribution between them. (See Figure 2.) The primary purpose of the spiked posts is to provide resistance to lateral loads by engaging the rock surface. The AFAR towers weigh 6 tons submerged; installation water depths are greater than 1000 feet.

(3) The Naval Underwater Center has established an underwater sound source resting on bare volcanic rock atop a seamount off Southern California. The steel frame, approximately ten feet square and weighing 5 - 7 tons, was placed at a 45-degree angle on the first try. The second bottom contact was near level, and performance has been satisfactory. The frame is supported by four steel legs capped with plates.[7]

Related Study - Seafloor Rock Microrelief

The Navy Electronics Laboratory (NEL) analyzed more than 700 NEL seafloor photographs, obtained in a wide variety of environments.[8] The NEL study showed rock outcrops and buried boulders commonly occurring on shallow and irregular underwater topographic features such as banks, island shelves, sides of troughs, seamounts, cliffs, ridges, canyons, marine terraces, and shelf breaks. Medium to coarse sands are usually present near the outcrops and show ripple marks, scour, banking, and other signs of water activity. Here the range of "microrelief" is from three centimeters (about one inch) to possibly as great as three meters (about ten feet), although all the photos of the NEL study showed "microrelief" of less than one meter (about three feet). "Microrelief" is defined as "the very small surficial topographic features that are superimposed on relief and are distinguishable by examination of bottom photographs."[8]

In summary then, even though exposed rock and near surface rock (herein defined as less than 25 feet of sediment cover) probably constitute only a very small percentage of the seafloor surface, that rock is generally located in strategic areas such that the Navy has already found it necessary to found seafloor structures on rock. Studies have examined seafloor rock microrelief and geological significance; but, as yet, these studies have not been applied to the problem of rock foundation design and performance prediction.

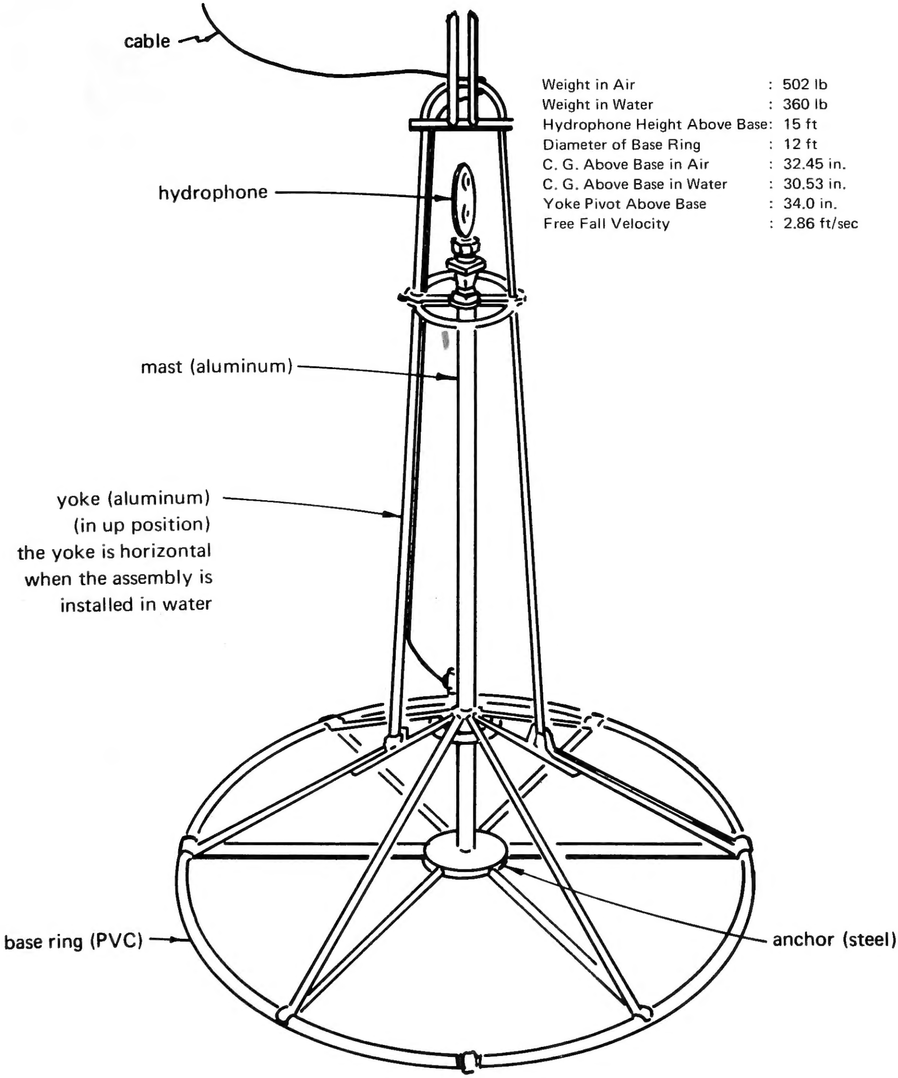

Figure 1. BARSTUR hydrophone assembly

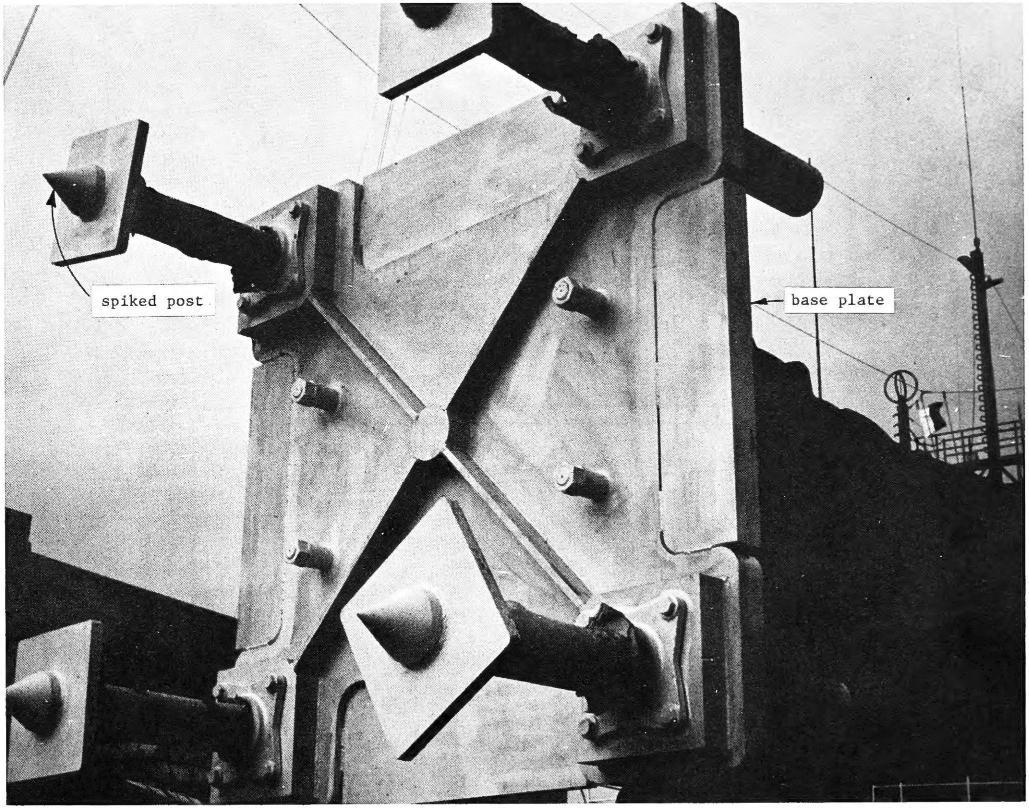

Figure 2. Project AFAR "November" tower before emplacement in vertical orientation

SEAFLOOR ROCK DESCRIPTION

Seafloor rock may be basalt, often coated with manganese; manganese precipitated as discrete nodules or coalesced into a continuous pavement; phosphate deposits as nodules or slabs; coral, both living and relict; and, on the continental shelves and slopes and on trench sides, the whole spectrum of known rock types.

Basalt

Occurrence. The ocean ridges and rises and submarine volcanoes are all composed of basalt. Many submarine volcanoes have built themselves up above the sea surface to form basaltic islands. Many others have become extinct while near the sea surface and later, while sinking relative to sea level, were capped by coral varying in thickness up to thousands of feet. Some idea of scale may be obtained from the overall dimensions for some seafloor features: the Mid-Atlantic Ridge has a height of 6000 feet above the deep basins on either side[2] with side slopes ranging up to 30 degrees, even at great depths;[3] volcanoes of the Pacific Basin reach 30,000 feet with side slopes up to 25 degrees.[9] From the rate of discovery and various other considerations it appears that there are approximately 10,000 volcanoes in the Pacific Basin with a relief of more than 1 km;[9] the Atlantic contains considerably fewer.[2]

Deep submarine basalt occurs as flows: the surface of these flows may be (1) a layer of "glass" fragments named hyaloclastite and/or (2) a mass of ellipsoidal bodies called pillow lava,[10] or (3) a bare coherent rock surface possibly representing a sheet flow as thin as 5 centimeters (1½ inches).[11] Hyaloclastites are sand-textured materials ranging from one millimeter to a few centimeters across, apparently formed through chilling and granulating of the front and surface of a lava flow advancing beneath water. This material chemically weathers to form a yellowish-brown earthy or waxy palagonite. Basaltic pillows are usually less than two meters (6.5 feet) in diameter, and most commonly less than one meter (three feet). Pillows may be tightly molded to each other, but commonly they are separated by detrital material, either ordinary sedimentary material or hyaloclastite. Whole pillows are commonly intermingled with fragments of pillows, typically resembling a wedge-shaped slice of watermelon. Some seafloor photos show large piles composed solely of such pillow fragments,[12] much like terrestrial talus piles. Pillow lavas quite commonly grade either laterally or vertically into non-pillowed flows.[10,13]

Lava erupted subaerially, or explosively erupted into shallow waters, may often ultimately reach depths of interest to the seafloor foundation engineer. Subaerial lava often flows into the sea; typical explosive products fall into the sea about erupting vents; and subaerially solidified lava often subsides relative to sea level reaching considerable water depths, as at Mauna Kea where formations are believed to have subsided 1000 meters relative to sealevel.[12]

The tops and probably much of the slopes of submarmine mountains are essentially areas of nonaccumulation because currents remove the fine pelagic sediments. Initial deposits have accumulated in hollows, small erosion channels, and between rock elements (i.e., erosional debris, pillows, etc.). When the surfaces have been filled nearly plane, currents keep them free of additional accumulation.[14] On some older seamounts, rock outcrops are so encrusted with manganese oxide that sampling of the bedrock is difficult.[15]

Engineering Significance. The performance of a foundation placed in this environment appears to depend most on the capability to find a reasonably level shelf and then to place the foundation on it: microrelief slopes of five degrees and possibly up to ten degrees can be accommodated, but not the maximum seamount and ridge slopes of 25 to 30 degrees. The problem is one of preventing downslope sliding; it is difficult to obtain purchase on slopes composed of pillows, pillow fragments, hyaloclastite, and intermingled sediments. Fortunately, near-level relief (microrelief less than three feet) does occur along the axes of mid-ocean ridges and rises, possibly in the summit craters of submarine volcanoes, and on wave cut benches and flat-topped seamounts.

A foundation in these areas will be required to resist large lateral loads from seafloor currents. The use of pointed legs to bear on the rock and engage it is not an ideal solution to the lateral load problem because such legs may penetrate between surficial pillows and pillow fragments or through sediment possibly resulting in greater deviation from level than that with a surface bearing plate. Legged foundations with integral bearing plates, as the AFAR towers, Figure 2, should serve much better.

Manganese Precipitates

Occurrence. Manganese deposits occur in varying degree and form in most oceans and in water depths from 25 to 20,000 feet. Significant manganese coatings may be found on rocks of older seamounts. Manganese deposits also occur as nodules and as "pavements" apparently over unconsolidated sediments. Spherical nodules range upward in size to about 20 cm (eight inches) as spheres, but flatter ones do occur ranging up to one meter (three feet) in diameter.[9] Nodule densities range from one or two per square meter to a tightly packed cobblestone mass.[16] Pavements of manganese concretion appearance are found, the most notable on the Blake Plateau. Thicknesses have not been measured, but tabular manganese slabs in the area were 20 to 30 cm thick and one-half to one meter across.[17]

Engineering Significance. Seafloor installations in nodule areas should employ spread footing type foundations,[18] although special consideration may have to be given to the problem of lateral load

resistance. Skirts, or cutting edges, used about the periphery of the foundation to hinder undercutting by animals or current scour, should push even 3-inch diameter nodules to the side. Pavements cannot be considered rock foundations because they may lie on unconsolidated material, and appreciable loads may punch through. Again, a spread footing type foundation is the logical selection, and again special consideration will have to be given to the problem of lateral load resistance. The pavement surface should be disturbed as little as possible because the same strong currents which keep these areas free of sediments will rapidly erode and undercut when possible.[17] If legged foundations, hereafter called "tined" foundations, are used in this environment (to resist lateral load), the tines themselves should not be depended on to support vertical load because they may punch through the pavement and find negligible resistance in the underlying sediment.

Coral

Occurrence. Perhaps one-half of the shores of the tropical Pacific and Indian Oceans are bordered by coral reef;[19] and a number of seamounts are capped by coral, sometimes reaching thousands of feet in thickness. Coral structures making up a reef vary greatly in size and shape; some are rounded, massive "heads" a few inches to several feet in diameter; others are delicate, branching forms named "staghorn"; there are numerous intermediate varieties. At the outer edges of a typical reef, pieces of living coral up to 20 feet across are torn off by storm waves. These are then either thrown up by the waves onto the reef flat, or they fall down onto the submarine slope outside the breakers. These coral pieces, if they come to rest within reach of sufficient sunlight (maximum depth about 90 fathoms[2]), may be subsequently bound together by living, thriving coral or, more likely, by calcareous algae. In this way a reef grows slowly outward at the margin.[19] Coral maintains a void space of 25 to 50 percent.[2]

The steep slope beyond the breakers may descend at 45 degrees to near vertical for a few fathoms, with a narrow shelf or a more gradual slope beyond. Beyond the shelf, slopes of as much as 45 degree to 200 meters depth are not uncommon, and they may reach 600 meters. Then slopes of approximately 25 degrees are common to 1000 fathoms.[2]

Engineering Significance. Coral slopes are undesirable sites for valuable, bottom-resting installations because of the steep slopes, the irregular microrelief resulting from large blocks, the highly variable strength of typical coral, and the potential for falling blocks from the reef above. Areas of small-sized coral debris and coral sand will occur and can be utilized for small, light-weight installations. The most dependable way to establish an installation on a deep coral slope appears to be to make the structure buoyant and anchor it.

Coral, when it occurs as a secondary formation, as for instance atop a non-submerged, subaerially-formed basalt flow, will grow usually as separate and distinct coral heads with spaces two feet across and up to four feet deep between. Again, positioning of level, stable foundations on such surfaces would be most difficult; it would be much simpler to relocate to nearby, more level areas.

Other Seafloor Rock

Rock is found in other seafloor environments: in submarine canyons, in deep-sea trenches, on fault scarps, and as erratics dropped to the seafloor. In the case of submarine canyons, rock often crops out on the walls. Rock types range from intrusive igneous, such as granite, through soft sedimentary.[2] Sediment creep, sediment flow, and turbidity currents are serious problems in submarine canyons and largely preclude canyons as sites for bottom-resting installations. Rock outcropping in the deep sea trenches is primarily igneous, ranging from basalts to peridotite and dunite, with some outcrops of fragmented or brecciated rock. Trench slopes are locally steep with pockets of angular talus.[20] Design considerations will include those for seamounts and ridges with the addition of earthquake and turbidity current considerations.[2]

Ice-rafted rocks occur often on the seafloor. Photographs from the Arctic show rocks occurring more often on higher ridges, presumably because higher current velocities minimize sediment deposition.[21] Photographs of the Thresher search area, at 2500 meters, from the base of the continental slope to the upper part of the continental rise, indicate that ten percent of the bottom area is made up of rocks, presumably ice-rafted. Most of the rocks are gravel to cobble-sized; boulders larger than one meter are not uncommon, and one photo shows a boulder exceeding three meters in diameter.[16] Foundation design in areas of ice-rafted rocks would appear similar to that in nodule areas.

Rock is also exposed in areas where permanent currents and tides prevent deposition or cause erosion. The Gulf Stream in crossing the Blake Plateau has had sufficient force to prevent deposition to 600 fathoms; sedimentary rocks of Tertiary age have been recovered. Tides have swept the floors of trenches in the Gulf of California, exposing a bed of boulders four meters in diameter at 400 fathoms.[2] The topography of these environments is essentially no different from that to be found on submarine volcanoes; however, the large currents do pose a significant lateral loading problem.

ROCK FOUNDATION CONCEPTS

The placement of a bottom-resting structure -- whether it be a 500-pound hydrophone or a 15-ton, 10-foot-high radioisotope thermoelectric generator -- on one of the seafloor rock environments described earlier, requires a foundation system to: (1) support the structure, (2) restrict and possibly prevent rocking motions, and (3) prevent

lateral movement. A conventional flat-plate foundation, even with cutting edges, will not often meet these requirements on an irregular rock surface.

Several rock foundation concepts have been briefly examined to determine their practicality. These are all variations of: (1) the embedded anchor, (2) the so-called tined foundation, (3) the crushable element foundation, and (4) the common deadweight anchor.

Embedded Anchor

The embedded anchor system provides vertical load, lateral load, and moment resistance, and it is workable in very irregular microrelief and on steep slopes. Propellant-embedded anchors have been installed with varying degrees of success in coral and in massive seafloor basalt[22] (see Figures 3a and 3b). Successful installation of anchor projectiles in hard brittle rocks, such as a competent basalt, may prove difficult because these rocks may shatter during the projectile penetration and the projectile find no purchase, or because, as has happened,[22] the projectile may crack during penetration. Further development of rock anchor projectiles and testing of their performance in various seafloor rock types are required before conclusions can be drawn. The propellant-embedded anchor is expected to find little purchase in pillow basalts because of the discrete nature of the blocks.

The use of the propellant-embedded projectile as a foundation element requires that the structure be tied down tightly; to accomplish this the capability must be developed to connect the structure and the embedded anchor projectile and then tighten the two together. Alternatively, the anchor launching unit and the structure could be made one; a properly designed non-sensitive structure would probably survive the shock wave and acceleration due to the slow-burning projectile propellant. Unfortunately, few structures important enough to be installed are non-sensitive. Further, a certain number of attempts will occur where the anchor misfires or the projectile does not embed properly; in these cases, the structure-anchor assembly would have to be raised to the surface to correct the malfunction. Preliminary analysis indicates that use of the propellant-embedded anchor as a tie-down for a seafloor foundation on rock involves a high probability of failure.

Alternately, a drilled-in and grouted pile provides a rigid foundation in a wide material range from a manganese pavement over dense sand to an integral basalt flow. The structure can be attached to the head of a standard anchor pile, and the drill-string passed through the center of the assembly (see Figure 4). This system does not require the capability to relocate a position on the seafloor, and it is considerably more capable of accommodating microrelief than any other system discussed herein. The use of drilled-in piles in deep water requires the services of an offshore drillship at $15,000+ per day; and, of the four drillships available to reach 6000 feet, all would require significant modification to be able to handle the structure and drill-in the

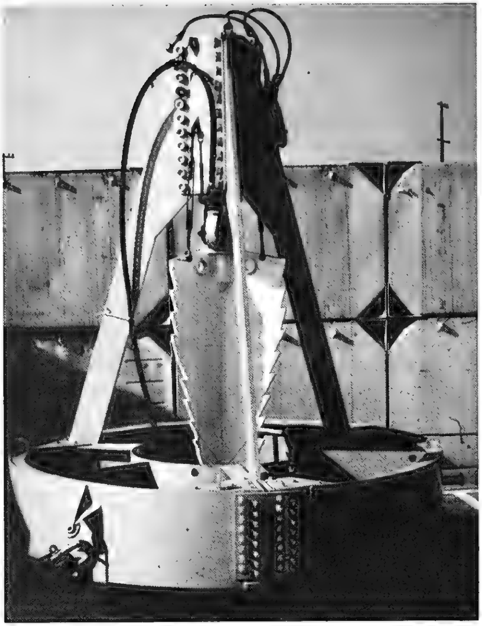

Figure 3a.

Propellant embedment anchor launch vehicle and test projectile

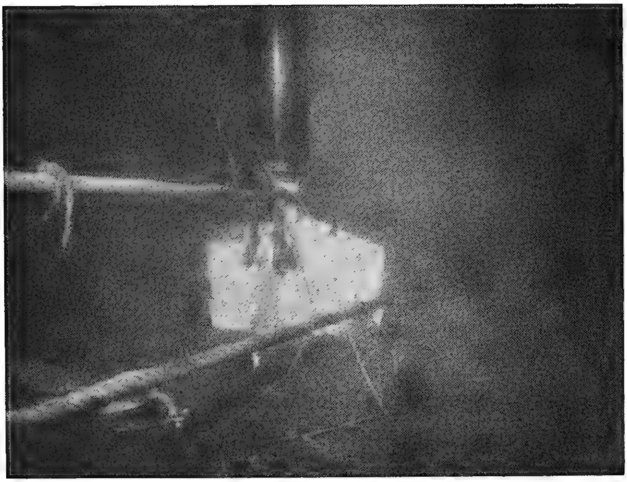

Figure 3b. Propellant embedment anchor rock projectile partially embedded in seafloor rock (Basalt)

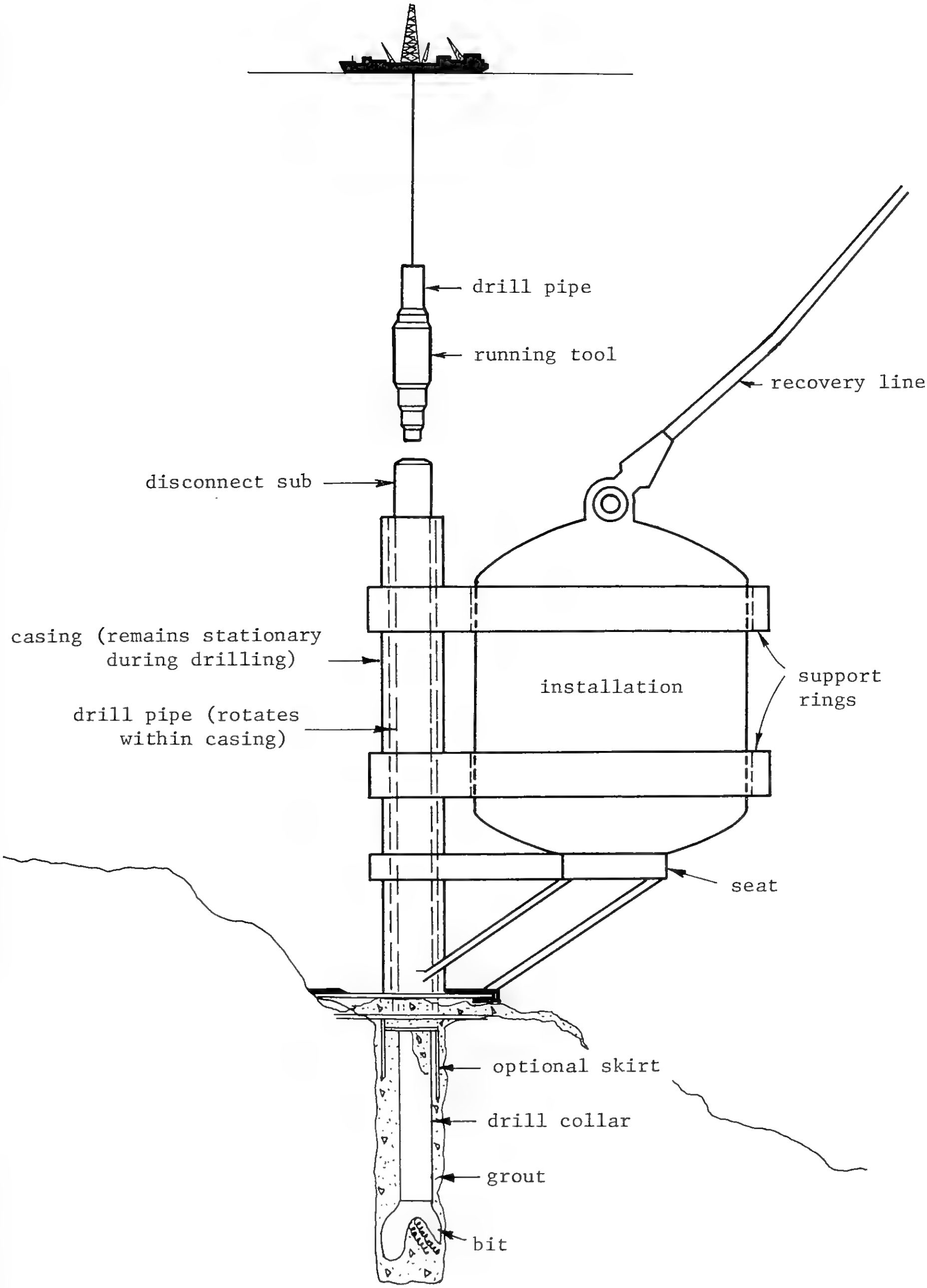

Figure 4. Drilled-in and grouted anchor pile foundation

pile. Thus, because of the limited number of vessels available, the high cost to the Navy, and the required equipment modifications and additions, the use of drilled-in pile foundations on rock is not expected to have great popularity in the near future.

Tined Foundation

The various tined foundation concepts all somewhat resemble the AFAR tower bases described earlier; however, the AFAR tower base functions more as a deadweight anchor with teeth. A "tine" is a tooth or prong aligned vertically or slightly inclined and is intended to provide vertical load support and to bite into rock irregularities to provide lateral load resistance.

Lightweight structures on rock may use only a three-legged arrangement (see Figure 5a). The center of gravity of the structure must be kept low to limit potential for overturning, and at the same time the frame and payload must be raised to clear the microrelief. Thus, such a foundation unit would probably be nine to 12 feet across with four feet of clearance between the frame and the tine tips; the tines would be solid steel, and the framework would be pipe-sections to assist in lowering the center of gravity. The tines should be inclined outward, possibly up to 20 degrees from the vertical, to reduce the joint bending moment due to initial implant tilt and to lateral loading. The tine collars, the flat, round plates attached about one foot up the tine, function as small footings if the tines should not encounter a solid rock surface. For instance, a tine could break through a weathered basalt surface into a lava tube, or it could bear in pillow basalt and encounter negligible resistance in the sedimentary fill between pillows. Such eventualities must be designed for because it is impossible in many cases to identify the real character of a rock surface even with good quality photographs; for instance, what appears as an integral flow surface may be a pillow lava.[16] Furthermore, a foundation may not be emplaced precisely at the position sampled and photographed, and bottom conditions change radically within short distances in rock outcrop terrain.

For larger, heavier, or tall structures, it may be necessary to use a greater number of tines, possibly arranged as illustrated in Figure 5b, dubbed a "multiple" stubby pile configuration. Here each cluster of tines would be articulated with respect to the main frame.

Alternately, each of the legs or tines could be made to emanate directly from the frame, and then in some way made to bear equally on the supporting strata. For instance, the tines could be floated as pistons in hydraulic cylinders, even remotely adjusted to level the structure, and then locked in place[23] (see Figure 5c). Or the tines may be allowed to deform in bending by inserting a limiting moment connection, a set of interleaved flat plates torqued together to produce a joint that will not move until some limiting moment is applied, after which the joint moves plastically until the applied moment

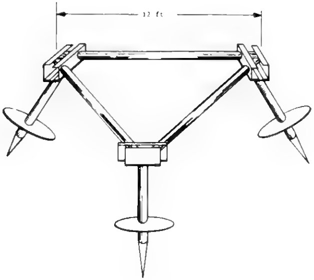

Figure 5a. Three-tined rock foundation concept

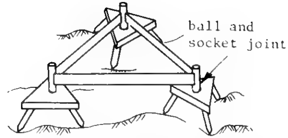

Figure 5b. Multiple-tined rock foundation concept

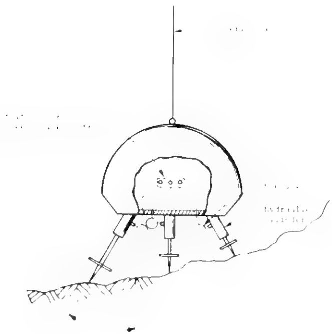

Figure 5c. Adjustable three-tined rock foundation concept (adapted from Reference 22)

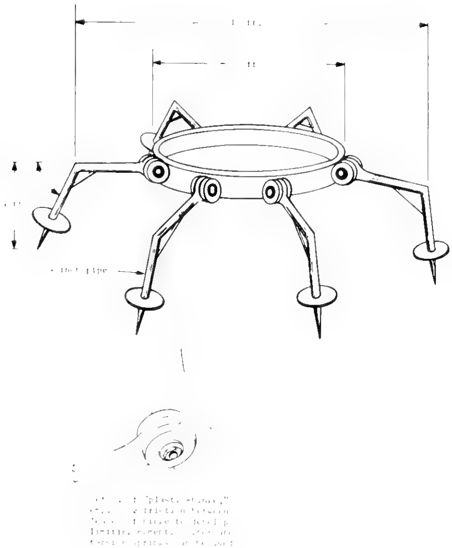

Figure 5d. Six legged "plastic-hinge" rock foundation concept

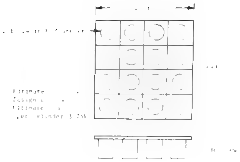

Figure 6a. Crushable foundation concept, vertical cylinders

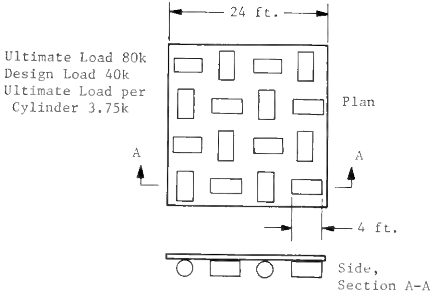

Figure 6b. Crushable foundation concept, 16 horizontal cylinders

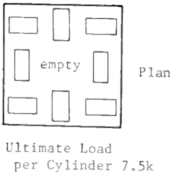

Figure 6c. Crushable foundation concept, 8 horizontal cylinders

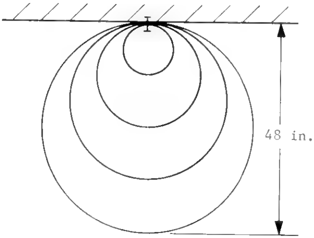

Figure 6d. Nested cylinders, crushable foundation concept

decreases once again to the limiting moment (see Figure 5d). Such a concept employing say six tines would provide a solution to the problem of the three-tined foundation that comes to rest with two tines high on exposed rock, the third penetrated deeply into soft ooze in a crevice where a single bearing collar is not sufficient. The multiple, plastic-legged form may be impractical because it may not be possible to develop a limiting moment connection with close moment tolerance, say 30 percent. Without such close moment tolerance the stiffer legs would end up supporting the structure alone, and the complex unit would be reduced in function to a plain three-tined affair.

Confirming calculations have not been made, but it is estimated that the "hydraulic" and "plastic-legged" concepts will weigh more per ton payload than the simpler three-legged and three-clustered varieties, because the intricacies will add weight without increasing capacity. A better approach to handling heavy loads appears to be to "ruggedize" the three-legged unit, attach a tilt sensor/indicator, and simply repeatedly pick-up and set-down the unit until a satisfactory attitude is indicated.

Crushable Element Foundation

The crushable element foundation was first conceived by engineers at the Naval Underwater Center for possible use with their underwater sound source mentioned earlier. Fifty-five-gallon oil drums, lying on their sides beneath the foundation plate, were to function as crushable elements to accommodate the microrelief of the rock surface and to provide interlock.

A brief search, as part of this report, was made for other materials or systems that would serve as crushable elements besides steel oil drums. Plastic foam-type materials were considered, but neither the closed-cell nor the open-cell materials suffice: with known closed-cell types, gas fills the cells, and the cells will collapse when subjected to the hydrostatic pressure during lowering to the seafloor (like a styrofoam cup); known open-cell types (like a sponge) will fill with seawater on the way down and will largely return to their original shape before contacting bottom; however, after contact they will provide insufficient rigidity. Although apparently not available now, it does seem likely that a plastic foam material having the required properties could be developed, considering the very wide range of foamed plastic materials available with varying rigidities, densities, pore sizes, and water absorption.

Plastic or glass spheres with small holes for pressure equalization do satisfy the requirements for a material that will not collapse with increase in hydrostatic pressure and yet will be rigid. Such spheres would be packed in a layer beneath the foundation plate and then solvent welded, glued, or epoxied at their contacts to hold the mass together. The problem with collapsing, tightly-packed spheres is that the first sphere of a layer to collapse derives much of its support

through arching against its neighbors; the second and third spheres collapse at progressively lower capacities because less support is given them through arching. Thus, a foundation underlain by crushable spheres will not exert uniform pressures on the bearing surface and may still have a tendency to rock.

A system of crushable, thin-walled, open-ended cylinders, illustrated in Figure 6, requires three and possibly four elements along any one line. Both axially and diametrically collapsing cylinders were analytically examined; axial collapse was predicted by the empirical thin-wall buckling formulas of reference 24, and diametric collapse was predicted via structural plastic design theory. Two materials were considered: mild steel and rigid polyvinyl chloride, PVC. The errors involved in applying the empirical buckling formula, which was developed for metals, to the PVC are expected to be small; however, test data are needed to verify this hypothesis. A preliminary design was carried through for a 40-kip, low-profile installation. Foundation size was governed by the cylinder size and configuration.

Figure 6a illustrates the configuration assumed for the axially-loaded cylinders, and Table I presents some preliminary analysis results. Reasonable cylinder diameters and wall thicknesses were selected, and allowable stresses were calculated from the buckling formula. The load capacity per steel cylinder, even for very thin-walled cylinders, is very high; therefore, steel cylinders of reasonable dimensions supporting the assumed 40-kip load would not properly collapse at points of load concentration to achieve conformity with the rock surface. Thus, axially-loaded steel cylinders are not suitable for eliminating foundation rocking. Cylinders made out of PVC perform much better with 1/16-inch wall cylinders having an ultimate of 4.8 kips versus 3.75 kips required ultimate. Again, these results are theoretical, and other failure modes, such as splitting, may control.

Figures 6b, 6c, and 6d illustrate the configurations which were assumed for diametrically loaded cylinders supporting a structure, that is, for cylinders lying on their side. The individual collapsible pod is made up of a number of progressively smaller cylinders to give the pod a somewhat constant load-carrying capacity through a considerable deflection. Thus, if the outermost 48-inch diameter cylinder were to develop plastic hinges, it would deform until the 36-inch diameter cylinder picked up the load, and so forth. For the analysis, the parameters selected were the foundation loading, the number of pods supporting each foundation, and the diameter of the outermost cylinder in the pods. From these parameters the outermost-cylinder wall thickness required by plastic design theory was calculated. An impact loading of 20 kips was added to the 40-kip foundation loading, for a total loading on the foundation of 60 kips. Two configurations having eight and sixteen pods respectively were selected. Table II indicates the wall thickness required to support the ultimate load for the two configurations: steel cylinders seem a viable contender for the eight-pod configuration; PVC cylinders appear to serve well for both eight- and

Table I. Load Capacity per Axially Loaded Cylinder, Failure by Buckling Symmetrical with Respect to the Cylinder Axis

Steel				
Cylinder diameter (in)	12	24	24	
Wall thickness (in)	1/16	1/16	1/32	
Allowable stress (ksi)	59	29	14.4	
Capacity per cylinder (kips)	(no buckling)	137	34	
Polyvinyl chloride				
Cylinder diameter (in)	12	12	24	24
Wall thickness (in)	1/16	1/8	1/16	1/8
Capacity per cylinder (kips)	4.8	19.0	4.8	19.0

Table II. Load Capacity of Diametrically Loaded Cylinders, Failure by Development of Plastic Hinges

Steel - 16 cylinder configuration (Figure 6b). Cylinder loading 3.75 kips ultimate				
Cylinder diameter (in)	48	36	24	12
Wall thickness (in)	.177	.153	.125	.088
Steel - 8 cylinder configuration (Figure 6c). Cylinder loading 7.5 kips ultimate				
Cylinder diameter (in)	48	36	24	12
Wall thickness (in)	.250	.217	.177	.125
PVC - 16 cylinder configuration. Cylinder loading 3.75 kips ultimate				
Cylinder diameter (in)	48	36	24	12
Wall thickness (in)	.373	.323	.263	.186
PVC - 8 cylinder configuration. Cylinder loading 7.5 kips ultimate				
Cylinder diameter (in)	48	36	24	12
Wall thickness (in)	.527	.456	.373	.263

sixteen-pod configurations. The use of steel cylinders for the sixteen-pod configuration results in undesirably thin cylinder walls. In the sea, corrosion would considerably reduce the percentage of steel section remaining and, as a result, considerably reduce the load capacity; thus, cathodic protection of the cylinders would probably be required. Because of this complication, the steel, sixteen-pod configuration was deemed undesirable. Other factors which may well prove determining, such as the effect of non-uniform load on a pod and the influence of lateral loads, are not amenable to analytical evaluation. However, based on this analysis it does appear that diametrically-loaded crushable cylinders are more practical than axially-loaded ones.

The concept of a crushable foundation deforming to shape itself over microrelief leads to another variation: consider a foundation underlain by an initially deformable material which first conforms to the seafloor surface and then later becomes rigid or "sets-up" as concrete. The setting materials could be grouts or plastics; the material could be contained beneath the foundation plate by a single membrane, by a number of sacks, or could be contained in a variety of reticulated foam. Reticulated foam is employed in military aircraft fuel tanks; the fuel can be pumped out of the tank, but it will not flow out under the influence of gravity.

In summary, it is feasible to fabricate a foundation having a crushable bearing surface that will accommodate a rock surface of considerable irregularity. Preliminary analysis indicates that PVC cylinders standing on their ends and PVC and steel cylinders lying on their sides will perform satisfactorily as the crushable elements. Other material/system concepts, which may also serve as a crushable, rigid element, but which are not sufficiently developed for present use, are a rigid, open-cell foamed plastic material and a grout with adjustable gel time contained beneath the foundation in flexible containers or in a reticulated foam.

Deadweight Anchor

A deadweight anchor or clump anchor may be as simple as a cube of concrete or an oblong slab of rock with an eye-ring set in for attachment.[25] The AFAR tower foundation described earlier is essentially an eight-foot-square steel deadweight anchor with a universal joint linking it to the 120-foot tower above; the four pointed steel feet serve to increase resistance to lateral sliding on the hard rock surface. For more compact installations, it is possible to modify the AFAR concept by adding a universal joint that "freezes" through corrosion or an explosive lock, thereby holding the installation rigid relative to the clump. The deadweight anchor may be further altered into a "coral" anchor by adding prongs, teeth, or appendages to engage the rock surface and increase resistance to lateral movement. However, depending on the environment, the clump characteristics, and the installation characteristics, the unit may rock considerably. Deadweight

anchors/foundations may serve quite well in many situations with small structures; however, for large structures, a deadweight foundation, to provide stability or fixity, will have to be excessively heavy.

EVALUATION

Most of the rock foundation systems evaluated are subject to distinct microrelief limits. These rock foundations must accommodate ten degree slopes (typical of basalt on seamounts) and microrelief of up to three feet. Figure 7 depicts these conditions, assuming a spread of 13 feet across the foundation framework and assuming the upslope contact point of the tripod bears on impenetrable microrelief three feet high. For the conditions depicted the installation is on the verge of being unstable but this is an extreme combination of circumstances; therefore, the design is reasonable. If conditions more extreme than ten degrees overall slope and one meter superimposed slope are expected, then tined and crushable element foundation systems will not survive; instead deadweight or embedded anchor systems are required.

For those environments where tined or crushable element foundations are thought applicable, it appears best to select a rigid-jointed, three-tined foundation system with tines tilted out 20 degrees and equipped with sand bearing collars one foot above the tips. Tined foundation systems with pods of tines at each of three corners are not as desirable because of potential improper alignment of the flexible-jointed pods. Crushable-element foundation systems are considered less desirable because of their limited lateral load resistance capability. Horizontal-lying, open-ended cylinders will have a difficult time engaging a smooth rock surface, even with cleats. The foundation underlain by grout or plastic does have special merit in that it does have potential to perform better than a tined foundation on pillow basalts, etc.; however, this system will require considerable development, such as a suitable grout or plastic, a containment system, a shipboard mixing system, and techniques for filling the grout container at sea. These development hurdles, when coupled with the fact that emplacement delays of any sort may result in the material setting-up or gelling before the foundation touches bottom, cause this system to lose appeal.

Because the selection of a foundation type is so highly dependent on the microrelief magnitude, a potential site must first be surveyed. Based on the survey data the percentage of microrelief less than three feet can be estimated, and thereby the probability of success of a tined or crushable element foundation determined. A deep-towed side-scan sonar system can be used for this survey work. The side-scan data can be used to develop a topographic map of the survey area; however, the resolution of the available towed systems (three feet)[26] is barely adequate for establishing the suitability of a site based on a three-foot microrelief criteria. Bottom stereo-photography is capable of providing improved resolution (per photograph, potentially to 0.3 inch);[26]

distance tine point to tine point 13 feet

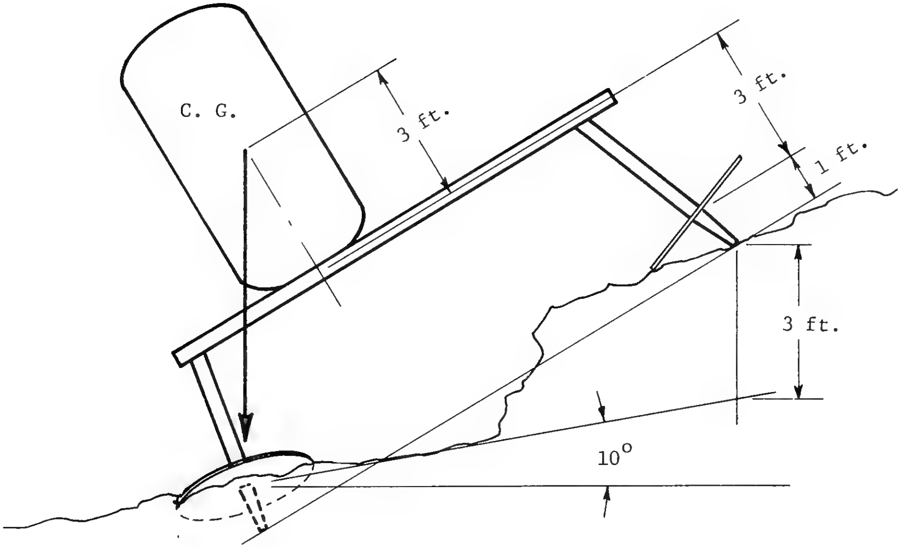

Figure 7. Limiting conditions, three-tined concept in state of incipient overturning

and, in addition, bottom stereophotography will provide more and better information about the surficial bottom material type and condition. In any case, when working with a unit to be lowered onto the seafloor, whether it have a tined foundation, crushable element foundation, or clump anchor with a universal joint to the structure, it is good practice to attach an attitude sensor/pinger to the foundation to give immediate information of unacceptable attitude. When warning is given, the unit can be picked up and re-implanted.

CONCLUSIONS

1. Bottom resting foundations are potentially suitable selections for seafloor sites having average slopes up to ten degrees and having microrelief magnitudes up to three feet. Tined or crushable element systems should serve well here. Accommodation of slope and microrelief combinations resulting in greater total foundation tilt will require using embedment or special deadweight anchors for stability.

2. In those situations where all of the foundation types discussed are permissible, weight should be given to the simple three-tined system with collars.

3. Foundations to be emplaced in an area of rock seafloor should be equipped with attitude sensor/pinger equipment, and the deployment technique should allow the unit to be picked up and moved to a new location.

4. The steeply sloping area off living and relict coral reefs is a "high risk zone" for seafloor structures. Only deadweight/clump foundation/anchors should be considered.

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13. ABSTRACT

The report identifies those rock foundation concepts most likely to succeed. Existing rock foundations are first described, previous peripheral studies are reviewed, and then a brief geologic review is made of seafloor rock characteristics. It is concluded that high resolution bathymetric information is essential to successful structure emplacement. For those sites where the slope is greater than ten degrees and the microrelief is in excess of three feet, deadweight/clump foundation/anchors should be used; otherwise the proper choice is a simple three-tined (legged) foundation framework.